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A STUDY ON THE DYNAMIC BEHAVIOUR OF THE COATING TEMPERED GLASS PLATE UNDER IMPACT

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ABSTRACT

When a film-coated glass plate is impacted by an external object, the strength of the glass under the film falls significantly, causing internal damage. A finite element program for impact analysis was developed to study the impact behaviour of general tempered glass and coated glass plate and its behaviour depending on the film thickness.

To this study, approaches based on a Whitney and Pagano's First-order Shear Deformation Theory (FSDT) associated with a generalized power law as a contact law is proposed, and the analysis, results are compared and reviewed with a wave propagation model and energy balance model to verify the accuracy of the analysis results. As a result of this study, the coated glass film is very effective in preventing impact. And also, although the presence or absence of coated film has a significant influence on impact behaviour, the size of the film thickness is not an important factor in impact behaviour.

KEYWORDS: Monolithic Glass (MG), Coating Glass (CG), Dynamic Behaviour & Finite Element

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Original Article

INTRODUCTION

When the coated glass panel such as exterior window glass is impacted by an external object, internal damage is caused, resulting in a significant reduction in structural strength. Therefore, the glass is protected by coating the film on the glass surface to reduce the impact stress on the glass by absorbing it from an external environment, such as outside weather and foreign object impact. And unlike monolithic glass, which is vulnerable to shock and destroy, coated glass can reduce the number of dangerous flying fragments by adhering on a film, substantially reducing the risk of injury to people. At the same time it can act as a barrier to penetration and can also contribute to the reduction of glass weight.

Coating tempered glass plate has been increasingly used in applications such as vehicles, buildings and electronic and protective coatings on engineering structures. However, despite their advantages, effective application is limited due to the difficulties in calculating the impact strength of film and glass at an optimal design stage that considered the impact. Most importantly, few publications offer direct impact response analysis, although impact damage from coated glass has been well studied.

The contact force F by impact has been related to the indentation by Hertzian contact law [1] and the modified Hertzian contact law [2]. However, when coated glass with a thin film adhered over the glass is

impacted, deformation and stress are very complicated. To analysis the impact behavior of coating glass with a thin film, the classic Hertzian contact law is not already valid in characterizing the contact force and indentation relation. In recent, Kurapati [3] suggested that a generalized power law (load-displacement curve) in coating glass plate vary with the film thickness and modulus. The effectiveness of this power law has been documented using the testing data from ABAQUS. The verification of the coded finite element program in conjunction with Sun's higher-order beam finite element and Kurapati's generalized power law as contact law has been already conducted to predict the overall impact responses of coating glass beam in several published papers, and their results showed good agreements with each other [4, 5].

In this study, a new impact plate finite element approach in conjunction with First-order Shear Deformation Theory (FSDT) and a generalized power law is applied to study the overall impact behaviour of coating glass. Dynamic behaviours such as contact force, deflection, dynamic energies and stresses due to changes in the film thickness of coating glass plate shall be obtained to study the effects of film thickness on impact. From these results, the dynamic behaviour of Coating Glass plate (CG) is compared with those of the Monolithic Glass plate (MG) with the same glass thickness. The effects of film thickness on coating glass plates are also to be studied.

FINITE ELEMENT SIMULATION

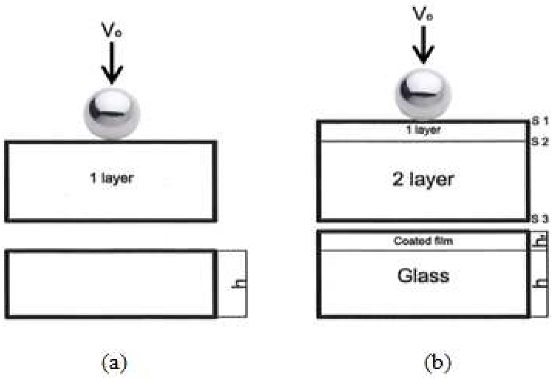


Figure 1: Schematic Diagram of (a) Monolithic Glass Plate (MG) and (b) Coating Glass Plate (CG)

Assume a MG with only the glass thickness h and a CG with the glass thickness h and film thickness hf, which is impacted externally by a steel ball of the radius R and the initial speed V_0, as shown in Figure 1. Where initial velocity is the speed at which the glass layer is not damaged.

Whitney and Pagano's FSDT [6] suggests that the displacement components at a point at any distance z from the reference plane are expressed as follows. The middle plane of the plate is taken as the reference plane of the model.

[FSDT]

$$u(x, y, z, t) = u_0(x, y, t) + z\varphi_x(x, y, t)$$

$$v(x, y, z, t) = v_0(x, y, t) + z\varphi_y(x, y, t) \quad (1)$$

$$w(x, y, z, t) = w_0(x, y, t)$$

where $(u_0, v_0, w_0, \varphi_x, \varphi_y)$ are unknown functions to be determined.

A generalized power law [3] of contact force and indentation relation by fitting data generated using a wide range of film/glass properties is given as follows

$$F=CE_s\delta^p \tag{2}$$

where F, δ, p and CEs are the contact force, indentation, power and contact stiffness, respectively.

Equation (2) represents that the contact force-deflection response for the indentation of any coating film/glass plate follows a general power law relation that is defined by the normalized film modulus (E_f/Es) and the normalized film thickness (h_f/R). To obtain the numerical analysis results of the impact responses on MG and CG, we applied a generalized power law other than the Hertzian contact law, Newton's second law and Newmark's integration scheme for solving the dynamic equations for each time. Similar simulation processes are discussed in detail in Ref. [4, 5].

Glass is a brittle material and therefore applies the law that the loading and unloading processes are treated as elastic. The glass plates are assumed to be impacted at the center by a steel ball impactor. The material properties of the target and impactor for simulation are shown in Table 1.

Table 1: Material Properties of Target and Impactor

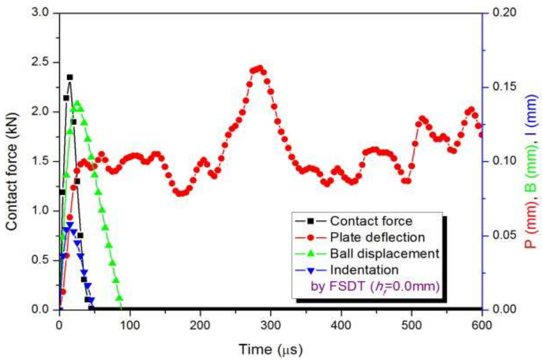
Materials		Properties
Target	Film (PET)	E_f=2.6GPa, ν_f=0.285, ρ_f=1,100kg/m^3 h_f=0.2, 0.4, 0.6mm
	Glass	E_s=70GPa, ν_s=0.23, ρ_s=2,440kg/m^3 h_s=4mm
Impactor		E=200GPa, ν=0.29, ρ_s=7,800kg/m^3 D=12.7mm, V_0=10m/s

RESULTS AND DISCUSSIONS

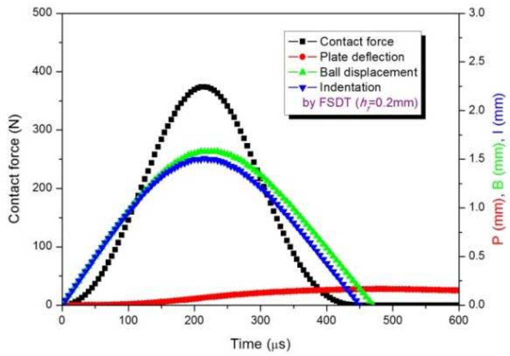
First, to verify the accuracy and reliability of this program, theoretical models (wave propagation model and energy balance model) [7] are presented in Table 2 by comparing the maximum contact force and contact duration. As a result, the maximum contact force shows a margin of error, but the overall trend is consistent, and the contact duration seems to be quite consistent. Figure 2 shows the results [the histories of contact forces, plate deflection, ball displacement and indentation for MG with glass (h=6mm), and CG with coating film (h_f=0.2, 0.4 and 0.6mm) and a glass of the same thickness] obtained from the present finite element analysis by FSDT at a velocity 10m/s. From Figure 2 it is shown that the maximum contact forces for MG and CG occur at 25µs and 220µs and the contact durations are 50µs and 440µs after the impact, respectively. The maximum deflection does not occur with maximum contact force. It presents a typical wave-controlled impact where the contact force and plate deflection are not on the same phase [8-9]. And also the maximum contact force at MG is about six times that of CG, and the maximum deflection at MG is similar to that of CG within 600µs after an impact. However, the contact duration for CG is much larger than for MG. In the case of CG, it is found that the variation in film thickness has little effect on the contact force, deflection and the contact duration.

Table 2: Comparison of Present Result and Wave Propagation Model and Energy Balance Model: (a) Max. Contact Force (b) Contact Duration

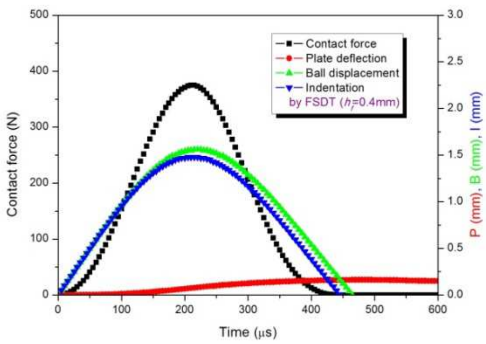
PET Thickness (mm)		(a) Max. Contact Force (N)		
		Present Result	Wave Propagation Model (WPM)	Energy Balance Model (EBM)
MG	0.0	2,350	2,320	5,200
CG	0.2	374	294	320
	0.4	375	304	328
	0.6	377	310	335
PET Thickness (mm)		**(b) Contact Duration (μs)**		
		Present Result	**Wave Propagation Model (WPM)**	**Energy Balance Model (EBM)**
MG	0.0	50.0	28.0	28.8
CG	0.2	450.0	469.0	469.0
	0.4	445.0	458.0	458.0
	0.6	440.0	448.0	448.0



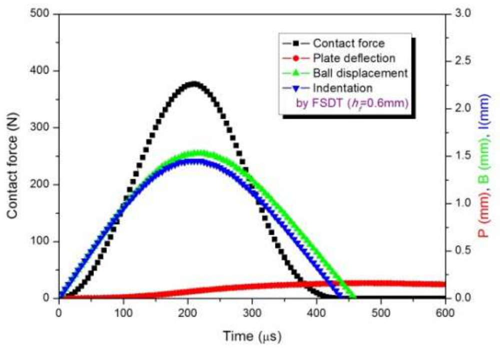
(a)



(b)



(c)



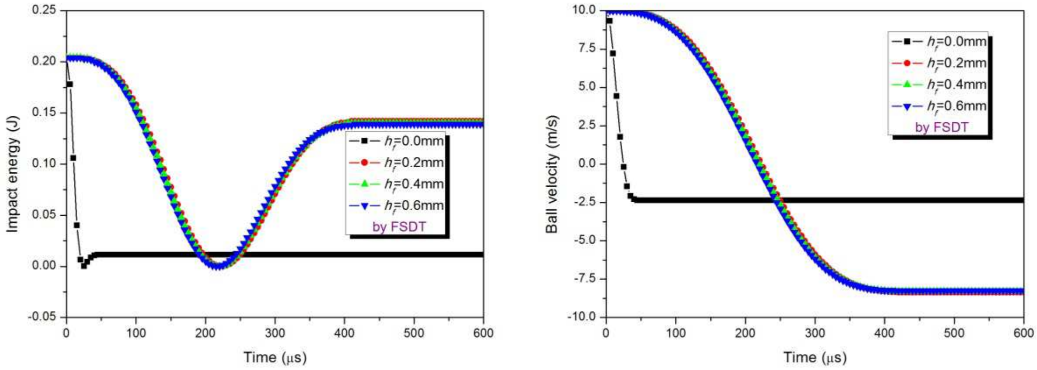
(d)

Figure 2: Histories of Contact Force and Deflection of MG and CG by Various Film Thicknesses

First, to verify the accuracy and reliability of this program, theoretical models (wave propagation model First, to verify the accuracy and reliability of this program, theoretical models (wave propagation model and energy balance model) [7] are presented in Table 2 by comparing the maximum contact force and the maximum deflection at MG is similar to that of CG within 600μs after an impact. However, the contact duration analysis results for energy and ball velocity histories are given in Figure 3. It shows that CG with the film thickness doesn't affects so much on energy and ball velocity histories unlike MG without film. A ball velocity of zero in Figure 3(b) minimizes impact energy in Figure 3(a), and a rise in energy from zero to plus in Figure 3(a) appears to increase the ball velocity from zero to minus in Figure 3(b). This is called

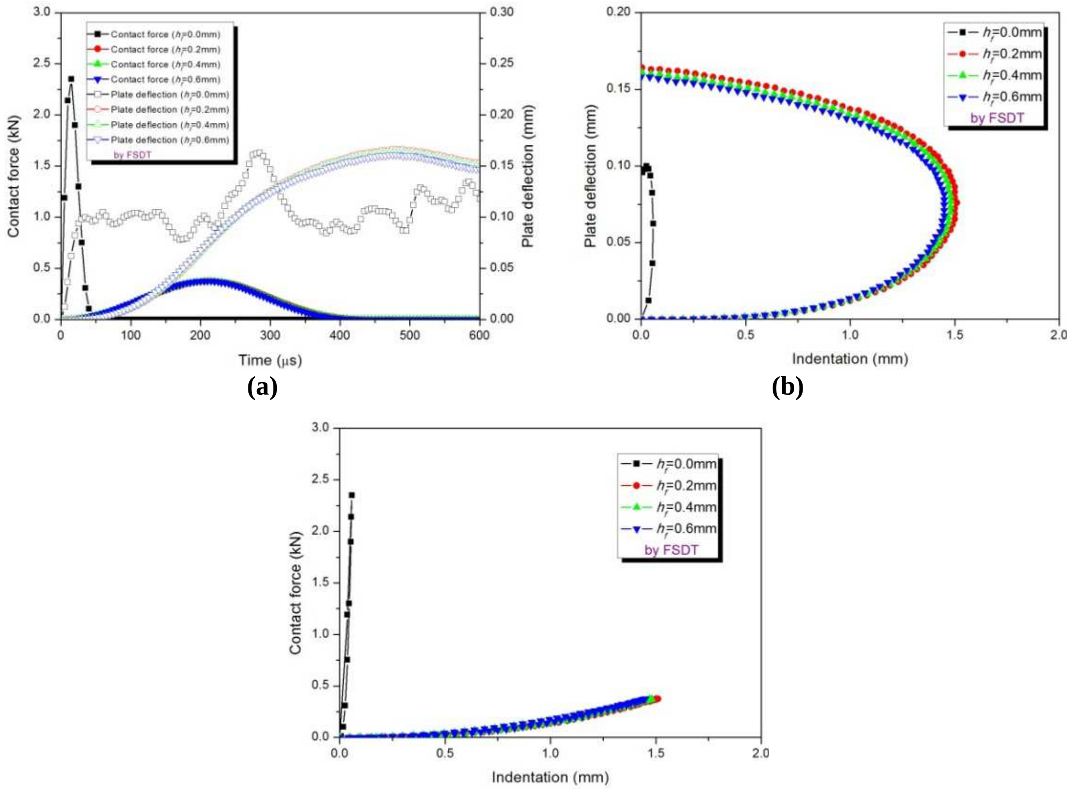
rebound energy, and the difference between initial energy and rebound energy becomes the absorption energy of the target. From Figure 3, we can see that rebound energy and rebound velocity of CG are much larger than those of MG, respectively, and that the effect of CG film thicknesses in terms of rebound energy and velocity is negligible.

Figure 4 depicts contact force-time, deflection-indentation and contact-indentation curves on MG and CGs by FSDT. While MG and CGs differ greatly in terms of contact force and deflection, they show little difference between CGs, respectively.



(a) **(b)**

Figure 3: The (a) Energy and (b) Velocity Histories of MG and CG



(a) **(b)**

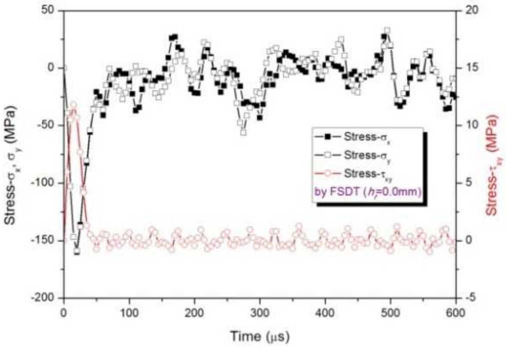
(c)

Figure 4: Relations of (a) Contact Force-Time, (b) Deflection-Indentation and (c) Contact Force-Indentation

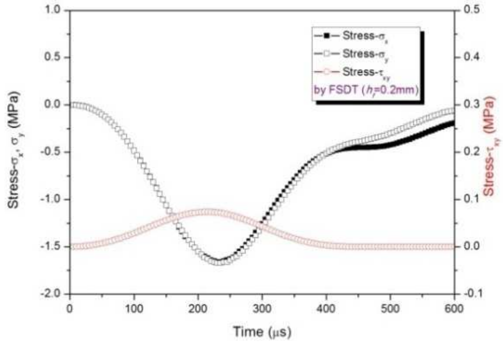
Figures 5(a) and (b) show the results of stress histories with MG and changes in the film thickness of CG by FSDT. From Figure (a), we can see that MG has a short period, and CG represents a very long period. This is due to the

low strength of the film over the CG material. Although the impact behaviour between MG and CG shows a large difference, the analysis results of film thickness changes of CG are not likely to show much variation. From Figure (c), all stress components by FSDT vary linearly through the thickness. And from the analysis results shown in Figure 5(c) show the discontinuance due to a significant difference of material properties between film and glass of CG. In case of MG without the film, the damage is rapidly carried out from the impacted surface to the opposite surface, but in case of film CG with film, the film absorbs the impact and greatly prevents the damage. In case of MG the maximum stress on both sides of the glass causes rapid damage, but in case of CG the minimum stress is generated at the top of the glass S2, below the impacted film, to minimize the damage.

Figure 6 shows three-dimensional stress distribution due to changes in the film thickness of MG and CG (h_f = 0.2 and 0.4mm) by FSDT, indicating that the magnitude of impact stress depends on the presence of the film and is not significantly affected by its thickness. It indicates that the impact absorption is very high due to a film effects in CG.



(a)



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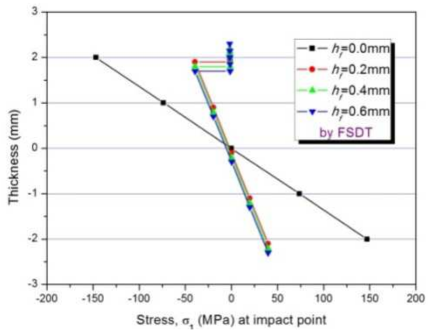
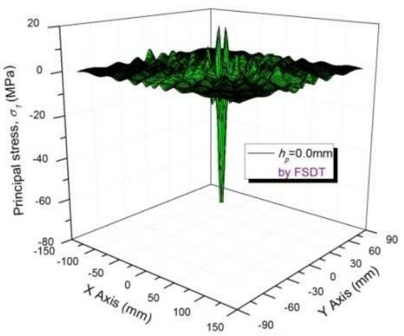
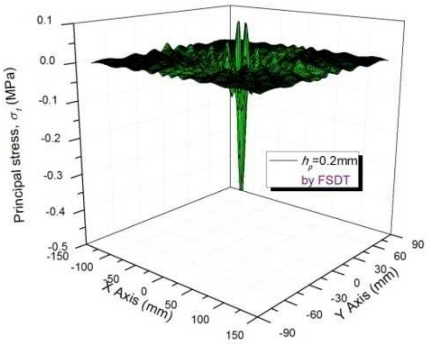


(c)

Figure 5: Stress Histories and Variations of Stress Through the Layer of MG and CG at Impact Point& Time of Max. force (h_f=0.0mm and h_f=0.0-0.6mm)



(a)



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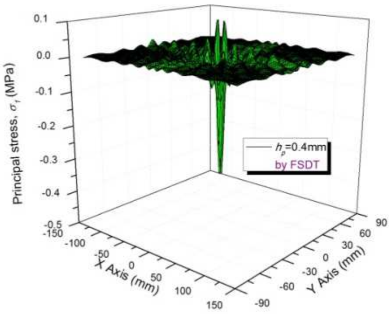
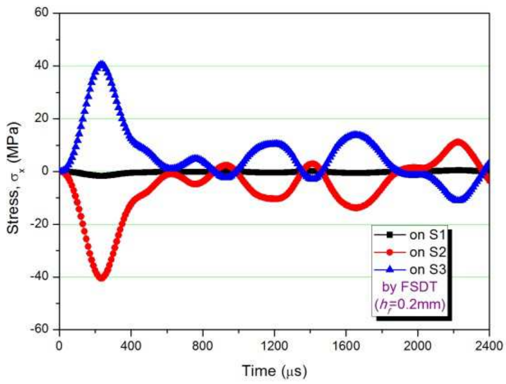
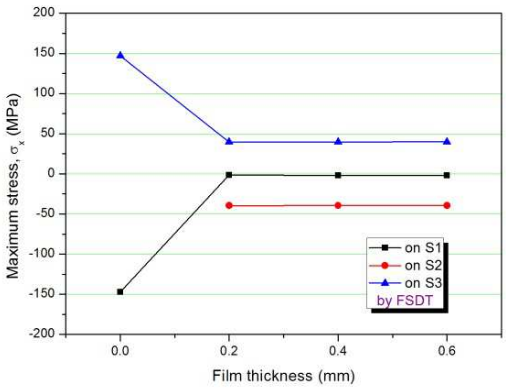


(c)

Figure 6: Variations of Principal Stress through Film Thickness



(a)



(b)

Figure 7: (a) Stress Histories and (b) Relation of Maximum Stress-Film Thickness of Each Layer of MG and CG

Figure 7(a) shows the results of stress changes caused by impact over time on each layer of CG material. Its results show maximum compression stress on the surface S2, maximum tension stress on the surface S3, and near zero stress on the surface S1. The maximum stress generated in CG represents half of the maximum stresses of the MG and thus quantitatively predicts the impact absorption effects of the film, which can contribute significantly. Figure 7(b) depicts the change in maximum stress on each surface to change in film thickness. From Figure 7(b) by FSDT, MG shows maximum (150MPa) and minimum (-150MPa) stresses on both sides of the glass since there is no film, and CG shows very small stresses (45MPa and -45MPa) on both sides of the glass as opposed to the film surface. And since there is little change in maximum stress, even after changing film thickness, it indicates that the presence of film in CG materials is very significant, but film thickness has not a significant influence in order to protect the glass from impact. It can be seen that this phenomenon is the same as the analytical result [10-12] for the effects of film on the laminated glass.

CONCLUSIONS

To predict accurately the impact behaviour of coating tempered glass due to foreign object impact both qualitative and quantitative, the new effective and powerful impact finite element approaches based on a Whitney and Pagano's First-order Shear Deformation Theory (FSDT) associated with a generalized power law is proposed, and two analysis results are compared and reviewed with a wave propagation model and energy balance model to verify the accuracy of the analysis results. The coated glass film serves as a function of protecting glass by increasing the deflection of the coated glass, reducing the contact force and minimizing the stress of the film lower glass surface. The coated glass film is very

effective in preventing impact. And also, although the presence or absence of coated film has a significant influence on impact behaviour, the size of the film thickness is not an important factor in impact behaviour. This study is believed to be very useful in predicting the quantitative and qualitative characteristics of all multi-layer structures by applying the impact analysis.

REFERENCES

1. *Goldsmith, W.(1960). Impact, Edward Arnold Ltd..*
2. *Yang, S. H. and Sun, C. T. (1982). Indentation Law for Composite Laminates, ASTM STP 787, DOI: 10.1520/STP28494S, (pp.425-449).*
3. *Kurapati, S. N. V. R. K., Lu, Y. C. and Yang, F.(2010). Indentation Load-Displacement Relations for the Spherical Indentation of Elastic Film/Substrate Structures, CMC (Computers, Materials & Contina), 20(10), (pp.1-17).*
4. *Kim, B. H., Ahn K. C. and Lee, C. W. (2014). Low Velocity Impact Behaviors of a Laminated Glass, Smart Science, 2(4), (pp.209-213).*
5. *Jung, D. S. and Ahn, K. C. (2015). Spherical Impact of Monolithic Glass Coated Exterior Film, J. of Korean Soc. of Mechanical Technology, 17(1), (pp.75-81).*
6. *Whitney, J. M. and Pagano, N. J. (1973). Shear Deformation in Heterogeneous Anisotropic Plates, Journal of Applied Mechanics, 40, (p.299).*
7. *Abrate. S. (2001). Modeling of Impacts on Composite Structures, Composite Structures, 51, (pp.129-138).*
8. *Aabid, A., Hrairi, M., Ali, J. S. M., & Abuzaid, A. Stress Concentration Analysis Of A Composite Patch On A Hole In An Isotropic Plate.*
9. *Olsson, R. (2003). Closed Form Prediction of Peak Load and Delamination Onset under Small Mass Impact, Composite Structures, 59(3), (pp.314-349).*
10. *Olsson, R. (2010). Analytical Model for Delamination Growth during Small Mass Impact on Plates, Int. J. of Solids and Structures, 47, (pp.2884-2892).*
11. *Ahn, K. C. (2017). Dynamic Prediction of Laminated Glass Plate Based on Higher-Order Plate Finite Element, Int. J. of Engineering & Technology IJMME-IJENS, 17(5), (pp.48-52).*
12. *Ahn, K. C. (2017). Microscopic Behaviors of Laminated Glass Plate Due to Foreign Object Impact, Int. J. of Applied Engineering Research, 12(21), (pp.11760-11764).*
13. *Ahn, K. C. (2015). Prediction of Wavefront on Laminated Composites due to Wave-controlled Impact, Int. J. of Engineering & Technology IJET-IJENS, 15(2), (pp.23-29).*